

# Lesson 3

## Gas-Phase Contacting Scrubbers

### Goal

To familiarize you with the operation, collection efficiency, and maintenance problems of gas-phase contacting scrubbers.

### Objectives

At the end of this lesson, you will be able to do the following:

1. List three gas-phase contacting scrubbers and briefly describe how each operates
2. For each scrubber above, identify the range of operating values for pressure drop, liquid-to-gas ratio, as well as the collection efficiency for both particulate and gaseous pollutants
3. Describe typical operating and maintenance problems associated with each gas-phase contacting scrubber design

**Video Presentation (optional):** If you have acquired the video titled, *Venturi Scrubbers: Operating Principles and Components*, please view it at the end of this lesson.

### Introduction

As mentioned in Lesson 1, wet scrubbers in this manual are categorized according to the manner in which the gas and liquid phases come into contact. This lesson, on gas-phase contacting scrubbers, begins your introduction to the many different scrubber designs covered in Lessons 3 through 6.

Gas-phase contacting scrubbers use the exhaust gas stream to provide the energy for gas-liquid contact. The exhaust stream moves across or through a liquid surface, shearing it to form tiny droplets. Breaking the liquid into fine droplets helps increase both particle and gas collection because the droplets provide targets on which the particles hit and are collected. They also provide a huge surface area for collecting (absorbing) gaseous pollutants. Thus, gas-phase contacting scrubbers can be used for both particles and gaseous pollutant collection.

A number of methods are used to provide this shearing action. The gas can be forced through constricted passages wetted with liquid, such as in venturi and orifice scrubbers. Or, the gas can be forced through cascades of liquid falling over flat plates as in plate tower

scrubbers. This lesson will focus on these collectors that work primarily by gas-phase contacting: venturi scrubbers, plate towers, and orifice scrubbers.

### Venturi Scrubbers

A **venturi scrubber** is designed to effectively use the energy from the exhaust stream to atomize the scrubbing liquid. Venturi devices have been used for over 100 years to measure fluid flow (Venturi tubes derived their name from G. B. Venturi, an Italian physicist). About 35 years ago, Johnstone (1949) and other researchers found that they could effectively use the venturi configuration to remove particles from an exhaust stream. Figure 3-1 illustrates the classic venturi configuration.

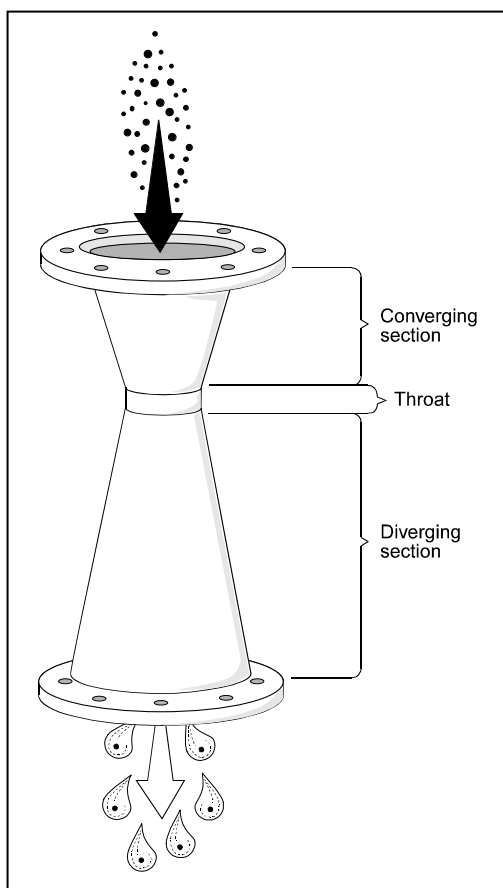


Figure 3-1. Venturi configuration

A venturi scrubber consists of three sections: a **converging section**, a **throat section**, and a **diverging section**. The exhaust stream enters the converging section and, as the area decreases, gas velocity increases. Liquid is introduced either at the throat or at the entrance to the converging section. The exhaust gas, forced to move at extremely high velocities in the small throat section, shears the liquid from its walls, producing an enormous number of very tiny droplets. Particle and gas removal occur in the throat section as the exhaust stream mixes with the fog of tiny liquid droplets. The exhaust stream then exits through the diverging

section, where it is forced to slow down. Venturis can be used to collect both particulate and gaseous pollutants, but they are more effective in removing particles than gaseous pollutants.

Liquid can be injected at the converging section or at the throat. Figure 3-2 shows liquid injected at the converging section. Thus, the liquid coats the venturi throat making it very effective for handling hot, dry exhaust gas that contains dust. Otherwise, the dust would have a tendency to cake on or abrade a dry throat. These venturis are sometimes referred to as having a **wetted** approach.

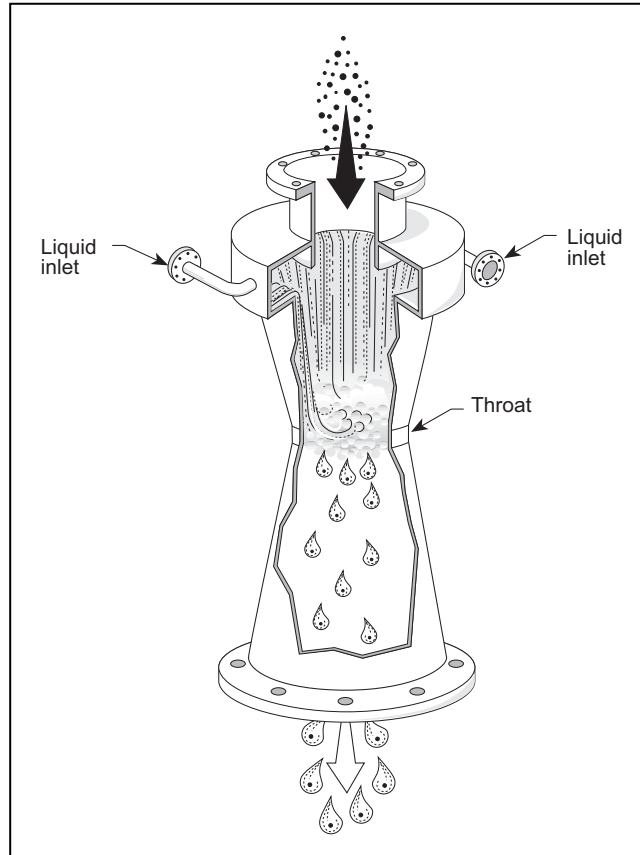


Figure 3-2. Venturi scrubber with a wetted throat

Figure 3-3 shows liquid injected at the venturi throat. Since it is sprayed at or just before the throat, it does not actually coat the throat surface. These throats are susceptible to solids buildup when the throat is dry. They are also susceptible to abrasion by dust particles. These venturis are best used when the exhaust stream is cool and moist. These venturis are referred to as having a **non-wetted** approach.

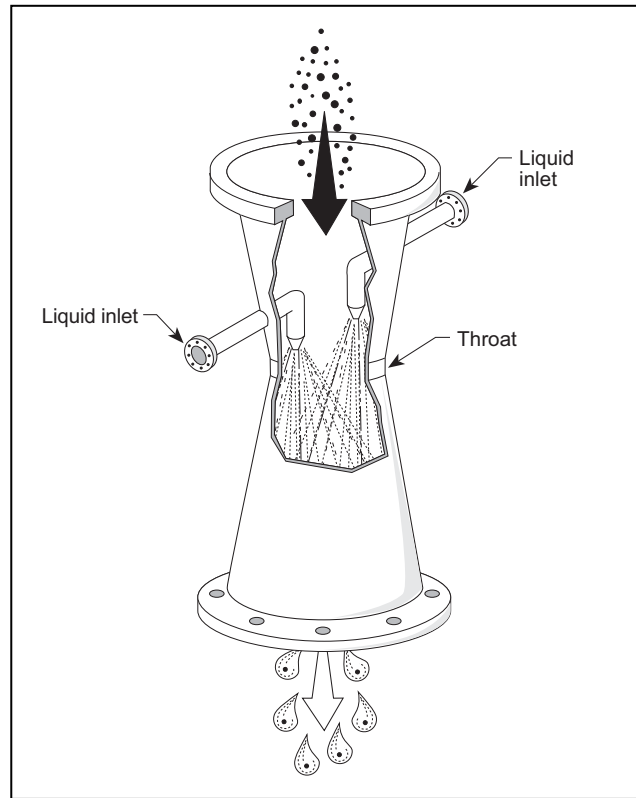


Figure 3-3. Venturi with throat sprays

Venturis with round throats (Figures 3-2 and 3-3) can handle exhaust flows as large as 88,000 m<sup>3</sup>/h (40,000 cfm) (Brady and Legatski 1977). At exhaust flow rates greater than this, achieving uniform liquid distribution is difficult, unless additional weirs or baffles are used. To handle large exhaust flows, scrubbers designed with long, narrow, rectangular throats (Figure 3-4) have been used.

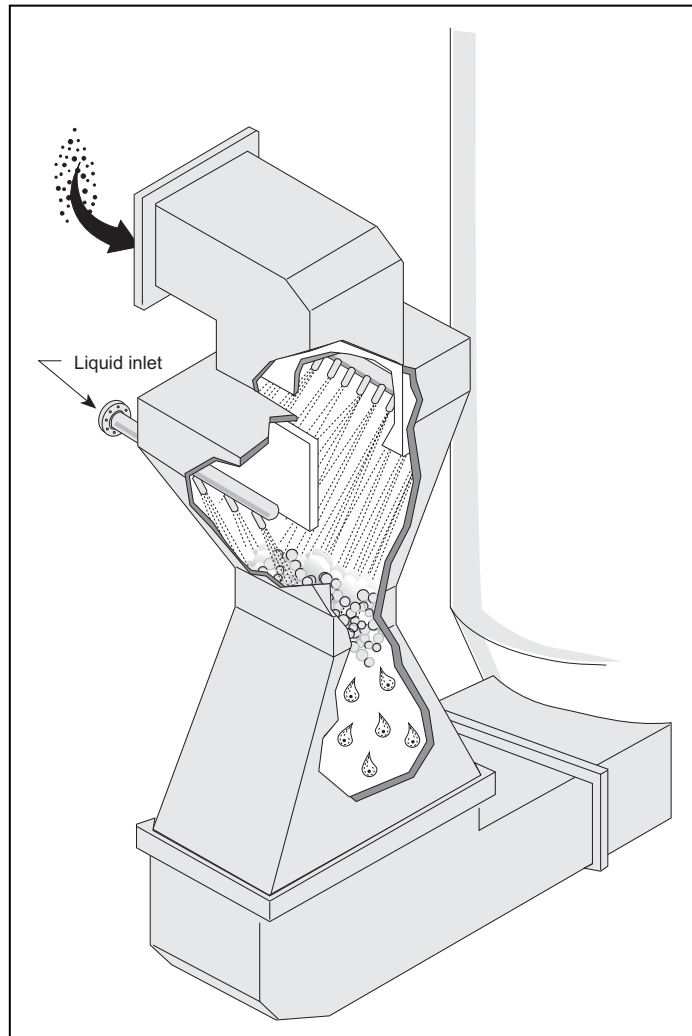


Figure 3-4. Spray venturi with rectangular throat

Simple venturis have fixed throat areas and cannot be used over a wide range of gas flow rates. Manufacturers have developed other modifications to the basic venturi design to maintain scrubber efficiency by changing the throat area for varying exhaust gas rates. Certain types of orifices (throat areas) that create more turbulence than a true venturi were found to be equally efficient for a given unit of energy consumed (McIlvaine Company 1974). Results of these findings led to the development of the **annular-orifice**, or **adjustable-throat**, venturi scrubber (Figure 3-5). The size of the throat area is varied by moving a plunger, or adjustable disk, up or down in the throat, thereby decreasing or increasing the annular opening. Gas flows through the annular opening and atomizes liquid that is sprayed onto the plunger or swirled in from the top.

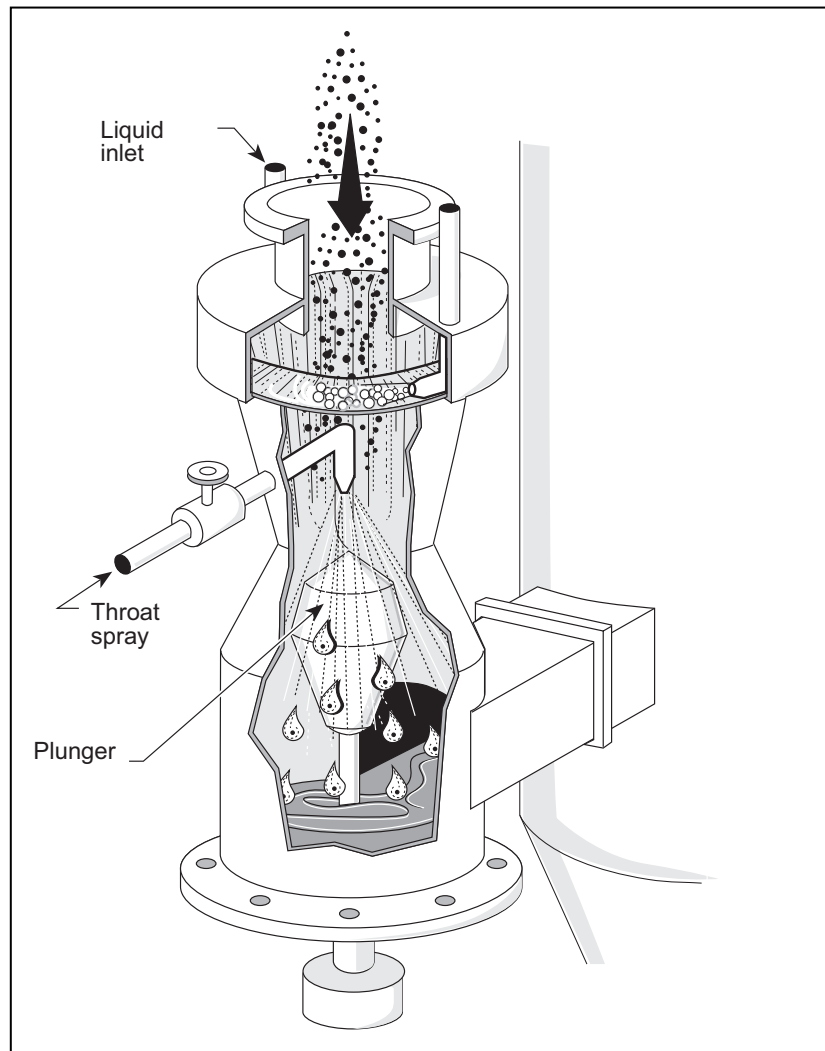


Figure 3-5. Adjustable-throat venturi with plunger

Another adjustable-throat venturi is shown in Figure 3-6. In this scrubber, the throat area is varied by using a **movable plate**. A water-wash spray is used to continually wash collected material from the plate.

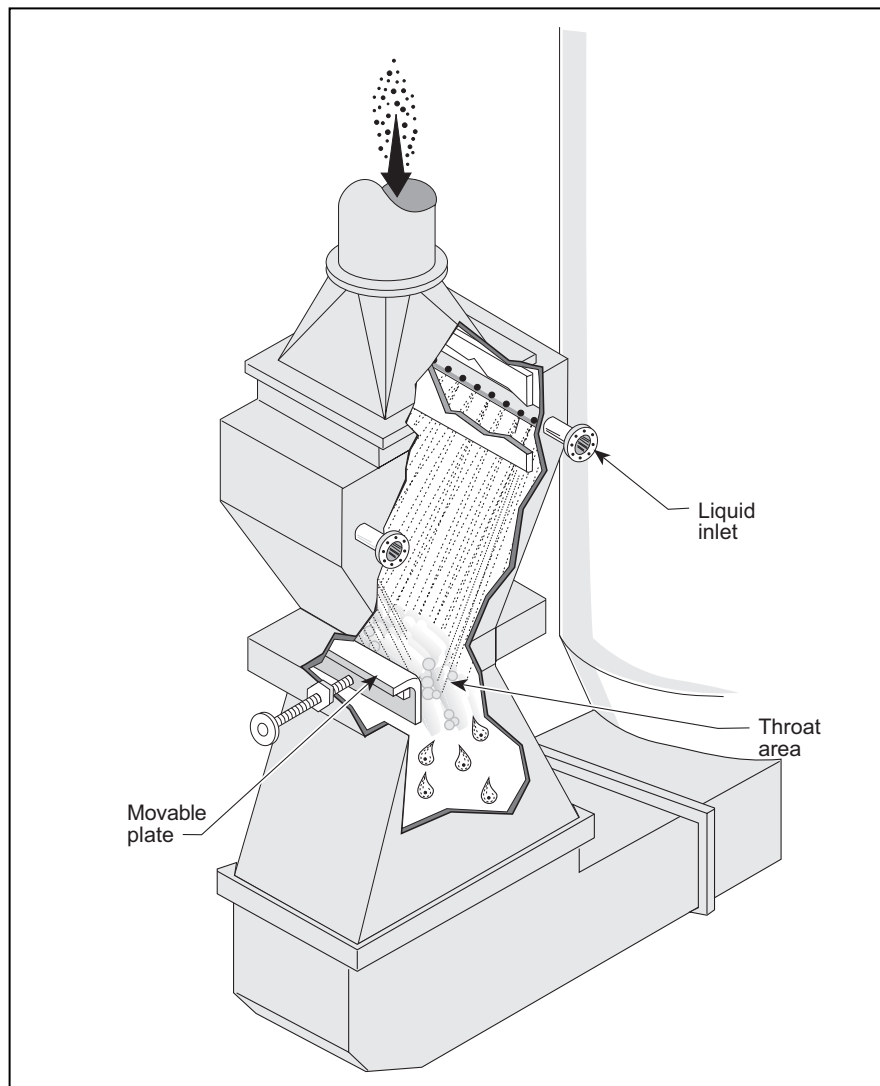


Figure 3-6. Adjustable-throat venturi with movable plate

Another modification can be seen in the **venturi-rod** or **rod deck** scrubber. By placing a number of pipes parallel to each other, a series of longitudinal venturi openings can be created as shown in Figure 3-7. The area between adjacent rods is a small venturi throat. Water sprays help prevent solids buildup. The principal atomization of the liquid occurs at the rods, where the high-velocity gas moving through spacings creates the small droplets necessary for fine particle collection. These rods must be made of abrasion-resistant material due to the high velocities present.

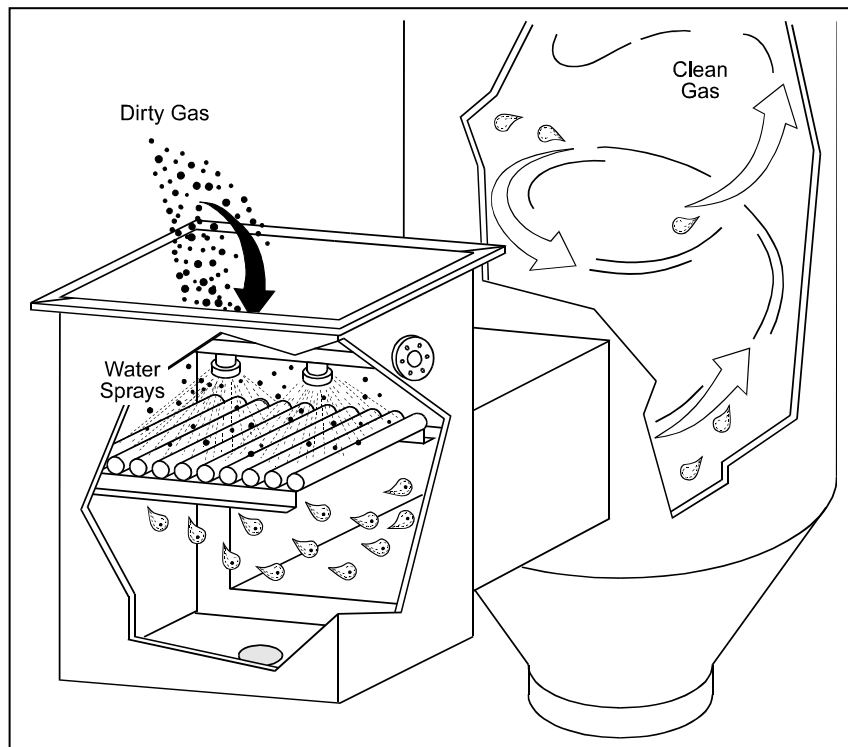


Figure 3-7. Venturi-rod scrubber

All venturi scrubbers require an **entrainment separator** because the high velocity of gas through the scrubber will have a tendency to exhaust the droplets with the clean gas stream. Cyclonic, mesh-pad, and blade separators (described in more detail in Lesson 8) are all used to remove liquid droplets from the flue gas and return the liquid to the scrubber water. Cyclonic separators, the most popular for use with venturi scrubbers, are connected to the venturi vessel by a flooded elbow (Figure 3-8). The liquid reduces abrasion of the elbow as the exhaust gas passes at high velocities from the venturi to the separator.



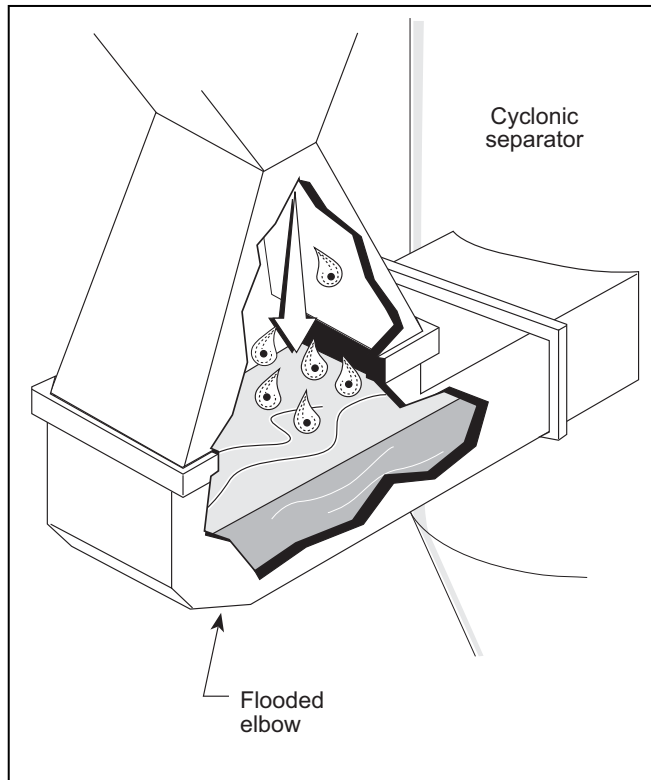


Figure 3-8. Flooded elbow leading into cyclonic separator

### **Particle Collection**

Venturis are the most commonly used scrubber for particle collection and are capable of achieving the highest particle collection efficiency of any wet scrubbing system. As the exhaust stream enters the throat, its velocity increases greatly, atomizing and turbulently mixing with any liquid present. The atomized liquid provides an enormous number of tiny droplets for the dust particles to impact on. These liquid droplets incorporating the particles must be removed from the scrubber exhaust stream, generally by cyclonic separators.

Particle removal efficiency increases with increasing pressure drop because of increased turbulence due to high gas velocity in the throat. Venturis can be operated with pressure drops ranging from 12 to 250 cm (5 to 100 in.) of water. Most venturis normally operate with pressure drops in the range of 50 to 150 cm (20 to 60 in.) of water. At these pressure drops, the gas velocity in the throat section is usually between 30 and 120 m/s (100 to 400 ft/sec), or approximately 270 mph at the high end. These high pressure drops result in high operating costs.

The liquid-injection rate, or liquid-to-gas ratio (L/G), also affects particle collection. The proper amount of liquid must be injected to provide adequate liquid coverage over the throat area and make up for any evaporation losses. If there is insufficient liquid, then

there will not be enough liquid targets to provide the required capture efficiency. Most venturi systems operate with an L/G ratio of 0.4 to 1.3 L/m<sup>3</sup> (3 to 10 gal/1000 ft<sup>3</sup>) (Brady and Legatski 1977). L/G ratios less than 0.4 L/m<sup>3</sup> (3 gal/1000 ft<sup>3</sup>) are usually not sufficient to cover the throat, and adding more than 1.3 L/m<sup>3</sup> (10 gal/1000 ft<sup>3</sup>) does not usually significantly improve particle collection efficiency.

### **Gas Collection**

Venturi scrubbers can be used for removing gaseous pollutants; however, they are not used when removal of gaseous pollutants is the only concern. The high exhaust gas velocities in a venturi result in a very short contact time between the liquid and gas phases. This short contact time limits gas absorption. However, because venturis have a relatively open design compared to other scrubbers, they are very useful for simultaneous gaseous and particulate pollutant removal, especially when:

- Scaling could be a problem
- A high concentration of dust is in the exhaust stream
- The dust is sticky or has a tendency to plug openings
- The gaseous contaminant is very soluble or chemically reactive with the liquid

To maximize the absorption of gases, venturis are designed to operate at a different set of conditions from those used to collect particles. The gas velocities are lower and the liquid-to-gas ratios are higher for absorption. For a given venturi design, if the gas velocity is decreased, then the pressure drop (resistance to flow) will also decrease and vice versa. Therefore, by reducing pressure drop, the gas velocity is decreased and the corresponding residence time is increased. Liquid-to-gas ratios for these gas absorption applications are approximately 2.7 to 5.3 L/m<sup>3</sup> (20 to 40 gal/1000 ft<sup>3</sup>). The reduction in gas velocity allows for a longer contact time between phases and better absorption. Increasing the liquid-to-gas ratio will increase the potential solubility of the pollutant in the liquid.

## Maintenance Problems

The primary maintenance problem for venturi scrubbers is wear, or abrasion, of the scrubber shell because of high gas velocities. Gas velocities in the throat can reach speeds of 430 km/h (270 mph). Particles and liquid droplets traveling at these speeds can rapidly erode the scrubber shell. Abrasion can be reduced by lining the throat with silicon carbide brick or fitting it with a replaceable liner. Abrasion can also occur downstream of the throat section. To reduce abrasion here, the elbow at the bottom of the scrubber (leading into the separator) can be flooded (i.e. filled with a pool of scrubbing liquid). Particles and droplets impact on the pool of liquid, reducing wear on the scrubber shell. Another technique to help reduce abrasion is to use a precleaner (i.e., quench sprays or cyclone) to remove the larger particles.

The method of liquid injection at the venturi throat can also cause problems. Spray nozzles are used for liquid distribution because they are more efficient (have a more effective spray pattern) for liquid injection than weirs. However, spray nozzles can easily plug when liquid is recirculated. Automatic or manual reamers can be used to correct this problem. However, when heavy liquid slurries (either viscous or particle-loaded) are recirculated, open-weir injection is often necessary. Table 3-1 summarizes some of the operational problems associated with venturi scrubbers.

**Table 3-1. Operational problems associated with venturi scrubbers**

Problem	Probable cause	Corrective action
Low efficiency	Low scrubbing-liquid flow rate	Check for plugged pipe or nozzles, incorrectly opened valves, or over-throttled pump-discharge valve.
	Low pressure drop	Check for low scrubbing liquor, low gas flow; inoperative or uncalibrated variable-throat controller; damaged variable-throat blade or disk.
	Partially blocked entrainment separator	Check washdown sprays, spray liquor composition, and pH (for scaling).
	Excessive gas flow	Check for damper setting or venturi throat setting.
	Inlet dust loading or particle size distribution different from that for which scrubber is designed	

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Table 3-1. (continued) problems associated with venturi scrubbers		Operational
Problem	Probable cause	Corrective action
High exit-gas temperature	Low scrubbing-liquid rate	Check for plugged pipe or nozzles, incorrectly opened valves, or over-throttled pump-discharge valve.
	High water-inlet temperature	Check and adjust makeup or heat-exchanger liquid flow rates.
	High inlet-gas temperature	Check quench sprays, if applicable, or upstream equipment.
Exhaust gas liquor entrainment	Plugged entrainment separator	Check washdown sprays and spray pattern; use more flushing periods if necessary. Check liquor chemistry for scaling agents.
	Plugged moisture-eliminator drain	Clean drain; add flushing water to continuously irrigate drain pipe.
	Excessive gas flow	Reduce gas flow.
Plugging or excessive wear of spray nozzles	Nozzle openings too small	Modify strainer/nozzle opening ratio so that nozzle holes are at least twice the diameter of strainer openings.
	Solids concentration too high in spray liquor	Check bleed line for malfunctions; check for excessive dust loading. Check strainers.
	Abrasives in spray liquor	Remove abrasives or install abrasion-resistant linings.
	Low pH in combination with abrasives is causing erosion or corrosion	Check separation equipment. Check for excessive dust loading in gas stream and for purge-line malfunctioning. Remove abrasives from liquor stream or install abrasion-resistant linings in wear zones. Add alkali for pH modification.
Excessive throat wear	High solids recirculation	Check bleed line for malfunctions. Check for excessive dust loading. Check strainers.
	Excessive gas velocity	Check throat pressure drop.
	Corrosion/erosion	Check separation equipment. Check for excessive dust loading in gas stream and for purge-line malfunctioning. Add alkali for pH modification. Install abrasion-resistant liners in high-wear zones if liquor modifications are not practical.

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<b>Table 3-1. (continued) problems associated with venturi scrubbers</b>		<b>Operational</b>
<b>Problem</b>	<b>Probable cause</b>	<b>Corrective action</b>
Erratic automatic-throat operation	Throat-mover malfunction Sensor signal incorrect  Damaged damper-disk mechanism	Remove from service; repair or replace  Check sensor taps for solids buildup. Check transmission tubing for liquid buildup or air leaks. Clean or repair sensor.  First make external inspection of drive train. If damaged area is not observed, shut unit down and make internal inspection using a throat-actuator manual override. Check for packing damage and excessively tight packing gland.
Low pressure drop	Broken, leaking, or plugged static-tap line Low gas-flow rate	Repair.  Check gas flow against design. Check and, if necessary, adjust fan belt or speed. Check inlet duct for obstructions.
Fan overloads and shuts off	Excessive flow rate through fan Low scrubbing-liquor flow rate	Check fan damper and variable-throat opening.  Check for plugged pipe or nozzles, incorrectly opened valves, or over-throttled pump-discharge valve.
Wet-dry interface buildup	Particle buildup where gas goes from unsaturated to saturated condition	Install special inlets. Reduce dissolved solids in scrubbing liquor. Devote routine maintenance to removal of buildup.

Sources: Kelly 1978 and Anderson 2000 Co.

## Summary

Venturi scrubbers can have the highest particle collection efficiencies (especially for very small particles) of any wet scrubbing system. They are the most widely used scrubbers because their open construction enables them to remove most particles without plugging or scaling. Venturis can also be used to absorb pollutant gases; however, they are not as efficient for this as are packed or plate towers (discussed later). The operating characteristics of venturi scrubbers are listed in Table 3-2.

Table 3-2. Operating characteristics of venturi scrubbers				
Pollutant	Pressure drop ( $\Delta p$ )	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure ( $p_L$ )	Removal efficiency (%)
Gases	13-250 cm of water (5-100 in. of water)	2.7-5.3 L/m <sup>3</sup> (20-40 gal/1000 ft <sup>3</sup> )	< 7-100 kPa (< 1-15 psig)	30-60% per venturi, depending on pollutant solubility
Particles	50-250 cm of water [50-100 cm of water is common] (20-100 in. of water) [20-60 in. of water is common]	0.4-2.7 L/m <sup>3</sup> (3.0-20.0 gal/1000 ft <sup>3</sup> )		[90-99% is typical]

Venturi scrubbers have been designed to collect particles at very high collection efficiencies, sometimes exceeding 99%. The ability of venturis to handle large exhaust volumes at high temperatures makes them very attractive to many industries; consequently, they are used to reduce particulate emissions in a number of industrial applications. This ability is particularly desirable for cement kiln emission reduction and for control of emissions from basic oxygen furnaces in the steel industry, where the exhaust gas enters the scrubber at temperatures greater than 350°C (660°F). Venturis are also used to control fly ash and sulfur dioxide emissions from industrial and utility boilers. A list of performance data for venturi scrubbers is given in Table 3-3.

Table 3-3. Performance data of typical venturi scrubbers				
Application	Dust	Typical particle-size range ( $\mu\text{m}$ )	$\Delta p$ (in. H <sub>2</sub> O)	Average collection efficiency (%)
<b>Iron and steel</b>				
Electric furnace	Ferro-manganese and ferro silicon	0.1-1.0	30-50	92-99
BOF	Iron oxide	0.5-2.0	40-60	98.5
Gray iron cupola	Iron, coke, and silica	0.1-10.0	30-50	95

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**Table 3-3. (continued)**  
**Performance data of typical venturi scrubbers**

Application	Dust	Typical particle-size range (μm)	Δp (in. H <sub>2</sub> O)	Average collection efficiency (%)
<b>Mineral products</b>				
Asphalt dryer	Limestone and rock	1.0-50.0	10-15	98
Lime kiln	Lime	1.0-50.0	15-25	99
Cement kiln	Cement	0.5-55.0	10-15	97
Crushing and screening areas	Rock	0.5-100.0	6-20	99.9
<b>Fertilizer manufacturing</b>				
Dryers	Ammonium chloride fumes	0.05-1.0	10-20	85
<b>Petroleum refining</b>				
Catalytic cracking unit	Catalyst dust	0.5-50.0	-	95
<b>Chemical</b>				
Spray dryers	Fumes and odor	-	20-60	-
Phosphoric acid plant	Acid mist	-	40-80	98
<b>Pulp and paper</b>				
Lime kiln	Soda ash	0.1-2.0	20-40	99
Recovery boiler	Salt particles	-	30-40	90
<b>Boilers</b>				
Coal pulverizer	Fly ash	20 (mass median)	15-40	97-99
Stoker	Fly ash	75 (mass median)	10-15	97-99

*To test your knowledge of the preceding section, answer the questions in Part I of the Review Exercise.*

## Plate Towers

A plate tower is a vertical column with one or more plates (trays) mounted horizontally inside. As shown in Figure 3-9, the exhaust stream enters at the bottom and flows upward, passing through openings in the plates. Liquid enters at the top of the tower, traveling across each plate to a downcomer through which it reaches either the next plate below or the bottom of the tower. Pollutant collection occurs on each plate as the exhaust gas stream contacts and then atomizes the liquid flowing over each plate. Plate towers are very effective in removing gaseous pollutants and can be used simultaneously for particle removal. Plate towers may not be appropriate when particle removal is the only consideration.

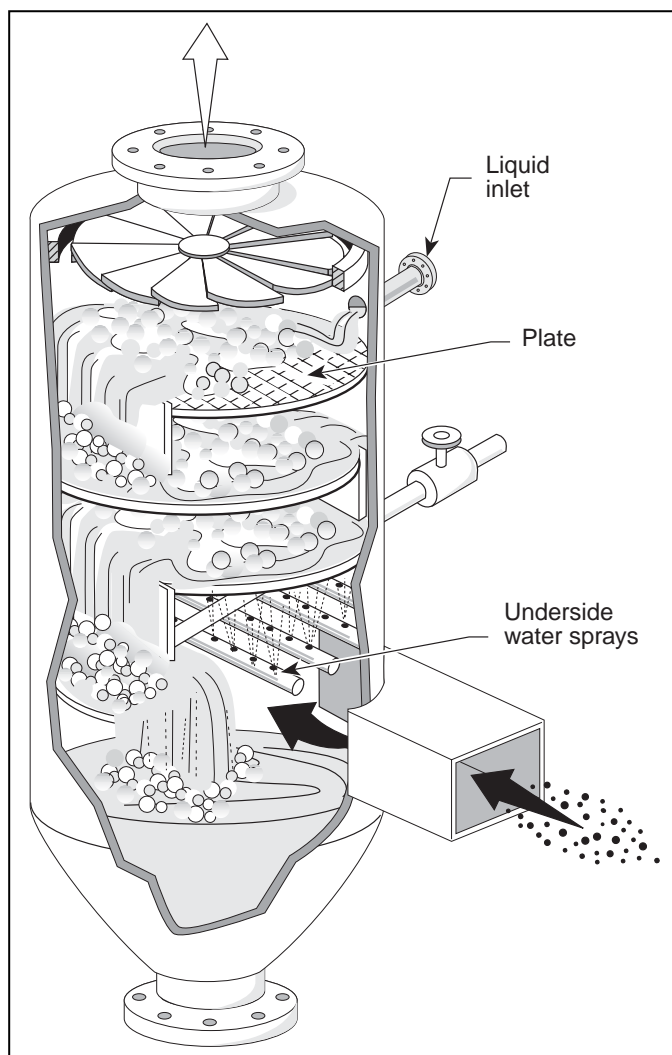


Figure 3-9. Plate tower



Plates, or trays, are designed in a variety of ways. The ones most commonly used for industrial sources are the sieve, impingement, bubble-cap, and valve. The sieve, impingement, and bubble-cap plates do not have moving parts, while the valve plates have liftable caps above the opening in the plate. Plate openings for the sieve plate can range from 0.32 to 2.50 cm (0.125 to 1.0 in.) in diameter. Openings for the other plate designs are generally larger.

**Sieve plates** contain approximately 1800 to 9000 holes per square meter (600 to 3000 per square foot) of surface. Exhaust gas rises through these small holes and contacts the liquid at the holes. The gas atomizes the liquid, forming a froth with droplets ranging from 10 to 100  $\mu\text{m}$  in diameter. Particle collection efficiency increases as the size of the sieve opening decreases. Smaller openings cause the gas velocity to increase thereby forming smaller droplets (collection targets). Sieve plates with large openings will not become plugged as easily as will other plate designs. Figure 3-10 depicts gas-liquid contact on a sieve plate.

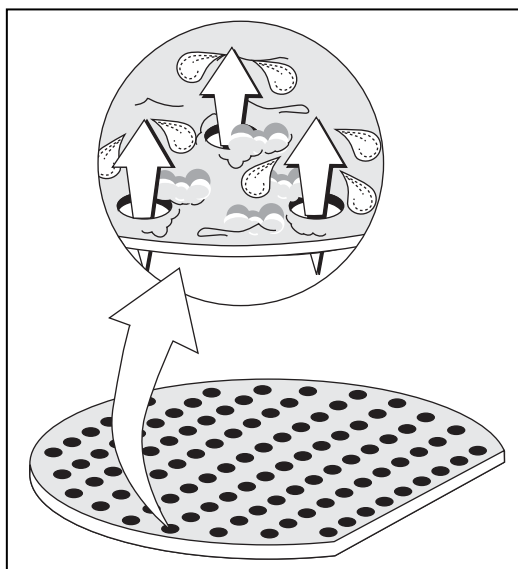


Figure 3-10. Sieve plate

**Impingement plates** are similar to sieve plates with the addition of an impaction target placed above each hole in the plate (Figure 3-11). The gas coming up through the hole forces the liquid on the plate up against the target (impingement surface). This design increases the mixing of the gas and liquid, provides an additional contact zone, and creates more liquid droplets.

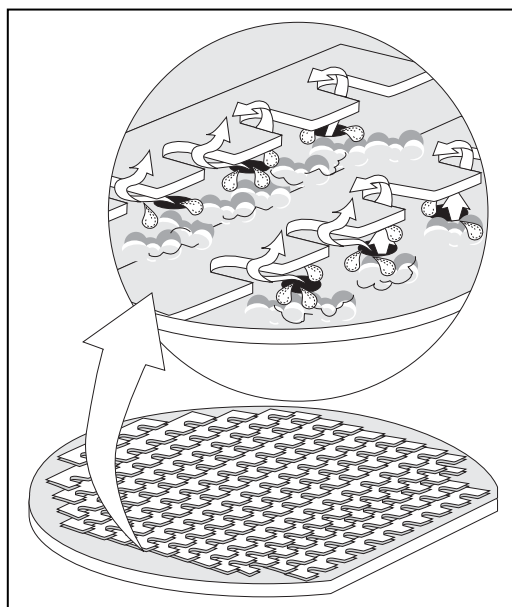


Figure 3-11. Impingement plate

In the **bubble-cap plate** design, the exhaust gas enters each cap through a riser around each hole in the plate and exits from several slots in each cap (Figure 3-12). This combination of caps and risers creates a bubbly froth that allows good gas-liquid mixing, regardless of the liquid-to-gas ratio. In addition, the caps provide a longer gas-liquid contact than either sieves or impingement plates, thus increasing absorption efficiency. Plugging and corrosion can be a problem for bubble-cap plates because of this more complex design.

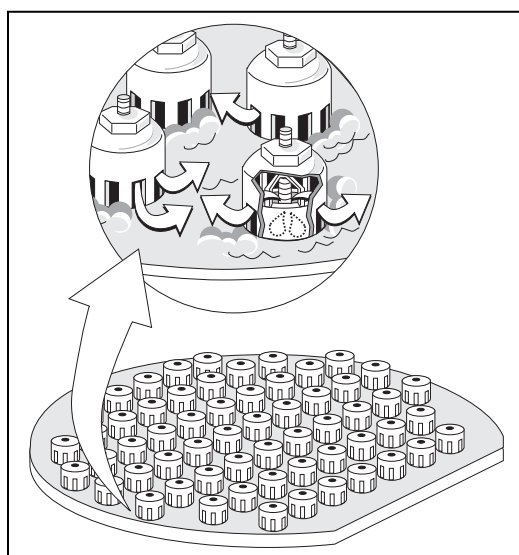


Figure 3-12. Bubble-cap plate

In the **valve plate** design, the exhaust gas passes through small holes in the plate, pushing up against a metal valve that covers each hole. The metal valve moves up and down with the gas flow. The valve is limited in its vertical movement by legs attached to the plate (Figure 3-13). Therefore, the liftable valve acts as a variable orifice. Caps are available in different weights to provide flexibility for varying exhaust gas flow rates. Floating valves increase gaseous pollutant collection efficiency by providing adequate gas-liquid contact time, regardless of the exhaust gas flow rate. This design is also suited for very small particle collection; however, valves will plug if large particles are in the exhaust stream. Wear and corrosion are also a problem for the retaining legs. Valve plates are more expensive than sieve and impingement plates, but less expensive than bubble-cap plates.

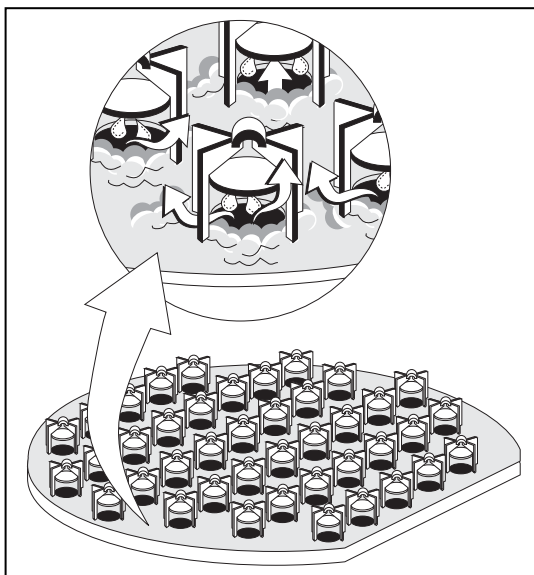


Figure 3-13. Valve plate

### **Particle Collection**

Particles are collected in plate towers as the exhaust gas atomizes the liquid flowing over the holes in the plates. The atomized droplets serve as impaction targets for the particles. Plate towers are considered to be medium-energy scrubbers having moderate particle collection efficiencies. Collection efficiency does not significantly increase by increasing the number of plates over two or three. Collection efficiency can be improved by decreasing the hole size and increasing the number of holes per plate. This produces more liquid droplets of a smaller size and increases the gas velocity through the plate. However, it also increases the pressure drop of the system.

### **Gas Collection**

Plate towers are very effective for removing gaseous pollutants from an exhaust stream. They can easily achieve greater than 98% removal in many applications. Absorption occurs as the exhaust stream bubbles up through the liquid on the plates and contacts the atomized liquid droplets. This action provides intimate contact between the exhaust gas and liquid streams, allowing the liquid on each plate to absorb the pollutant gas. Each plate acts as a separate absorption stage; therefore, absorption efficiency can be increased by adding plates. Absorption efficiency can also be improved by adding more liquid or by increasing the pressure drop across each plate, which increases gas-liquid contact.

### **Maintenance Problems**

Plate towers are susceptible to plugging and/or scale-buildup problems. If the exhaust stream contains a high concentration of dust or sticky materials, plate towers are generally not used. To clean the plates, access ports to each one are usually installed. In some systems, plates can actually be removed for cleaning. In addition, water sprays can be used to spray the underside of the lowest plate in the tower to eliminate the possibility of a **wet-dry interface**. If surfaces are not totally dry or wet, particles in these transition areas tend to become sticky and cause plugging.

Gas-liquid distribution may also be a problem with plate towers. First, if the plates are not level, gas-liquid contact will be reduced thus reducing collection efficiency. Second, a condition known as **flooding** (liquid buildup on a plate) can occur if either the liquid-injection or exhaust gas velocity is excessive, which will cause liquid to "stand" on the top of a plate. Flooding causes an increase in pressure drop and a decrease in gas-liquid mixing. **Weeping** (liquid dripping through the holes in the plates) can occur if the gas velocity is too low. Weeping also reduces gas-liquid contact. Table 3-4 summarizes some of the operational problems associated with plate towers.

**Table 3-4. Operational problems associated with plate towers**

Problem	Probable cause	Corrective action
Weeping	Too large an open area (holes) on tray Gas rate lower than design	Try bleeding in excess air or blocking off excess area. Check and adjust fan belt or speed. Check inlet duct for obstructions.
Flooding	Excessive liquid injected onto a plate Excessive gas flowing through a plate, causing the liquid to "stand" on a plate	Reduce the liquid-injection rate. Reduce the gas flow rate, if possible. If the gas flow rate is set because of process conditions (and it is excessive), an increase in tower design (size) may be necessary.
Plugging	High solids concentration in scrubbing liquor  Little or no water flow to trays  Higher-than-expected particle content in inlet gas Scale buildup	Check percentage of solids in recycle liquid. Check solid-separation equipment on recycle liquor. Use spray wash header. Clean trays periodically. Check pump output; look for plugged piping, nozzles, incorrectly opened valves, or overthrottled pump-discharge valves. Add prequench sprays. Use a low-pH wash periodically to dissolve scale.
Poor liquid distribution	Trays not level Liquid flow rate too high or gas flow rate too low  Mechanical problems with trays	Check and level. Check pump output; look for plugged piping, nozzles, incorrectly opened valves, or overthrottled pump-discharge valves. Check for warped trays, loose fittings, and loose or broken baffle strips or caps.

Sources: Kelly 1978 and Buonicore 1982.

## Summary

Plate towers are used most often when gaseous pollutant removal is the major concern. They can achieve greater than 98% collection efficiency, depending on the solubility of the gaseous pollutant. They can also be used to collect particles, but plugging and scale buildup problems may occur.

Plate towers are used successfully in flue gas desulfurization systems to remove sulfur dioxide emissions from utility boilers. They are also used to reduce pollutants emitted from petroleum refineries, chemical processes, acid manufacturing plants, and metal smelters. A summary of the operating characteristics of plate towers is given in Table 3-5.

Table 3-5. Operating characteristics of plate towers					
Pollutant	Pressure drop ( $\Delta p$ )	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure ( $p_L$ )	Removal efficiency	Applications
Gases	2.5-20 cm of water per tray (1-8 in. of water)	0.7-2.0 L/m <sup>3</sup> (5-15 gal/1000 ft <sup>3</sup> )	< 34.5 kPa (< 5 psig)	Very effective (> 98%), depending on the solubility of the gaseous pollutant	Coal dryers Copper roasting Industrial boilers Chemical process industries Petroleum refineries
Particles	[Normal pressure drops are 7.6 cm (3 in.) of water]	0.3-0.7 L/m <sup>3</sup> (2-5 gal/1000 ft <sup>3</sup> )		> 1.0 $\mu$ m diameter	Incineration processes

*To test your knowledge of the preceding section, answer the questions in Part 2 of the Review Exercise.*

## Orifice Scrubbers

In orifice scrubbers, the exhaust stream from the process is forced through a pool of liquid, usually water. The exhaust stream moves through restricted passages, or orifices, to disperse and atomize the water into droplets. These scrubbers are also called *self-induced spray*, *inertial*, or *submerged orifice scrubbers*.

Several orifice scrubbers designs are typically used. In each, the incoming exhaust stream is directed across or through a pool of water as shown in Figure 3-14. The high exhaust stream velocity, approximately 15.2 m/s (50 ft/sec), creates a large number of liquid droplets. Both particles and gaseous pollutants are collected as they are forced through the liquid pool and impact the droplets. However, these scrubbers are generally used for removing particles. Large particles are collected when they impact the liquid pool or its surface. Small particles are collected when they impact the droplets. Baffles, or air foils, are added to provide turbulent mixing of the exhaust stream and droplets.

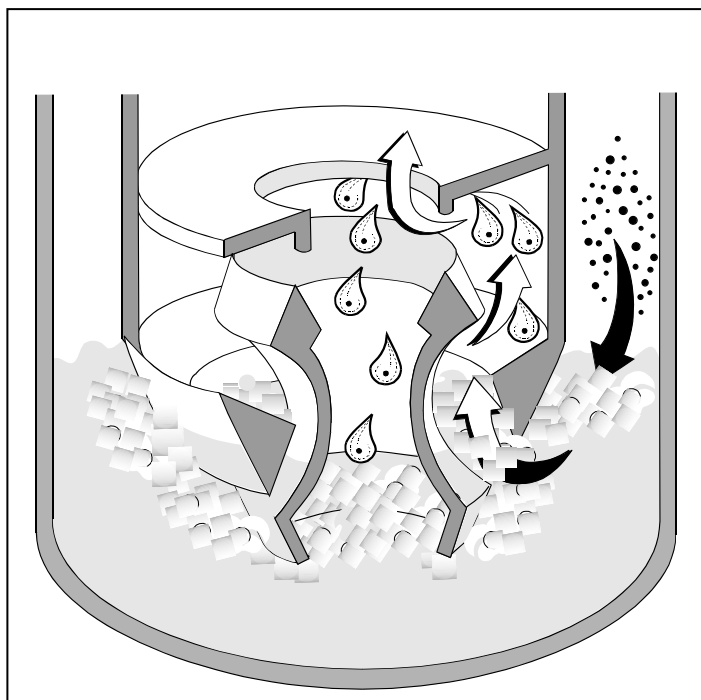


Figure 3-14. Detail of orifice action

In the *self-induced spray scrubber*, the exhaust stream enters through a duct as shown in Figure 3-15. The exhaust stream is forced by baffles through a pool of liquid. Particles and gases are collected in the pool and by the droplets. Additional baffles placed in the path of the "clean" exhaust stream as it exits the vessel serve as impingement surfaces to remove entrained droplets.

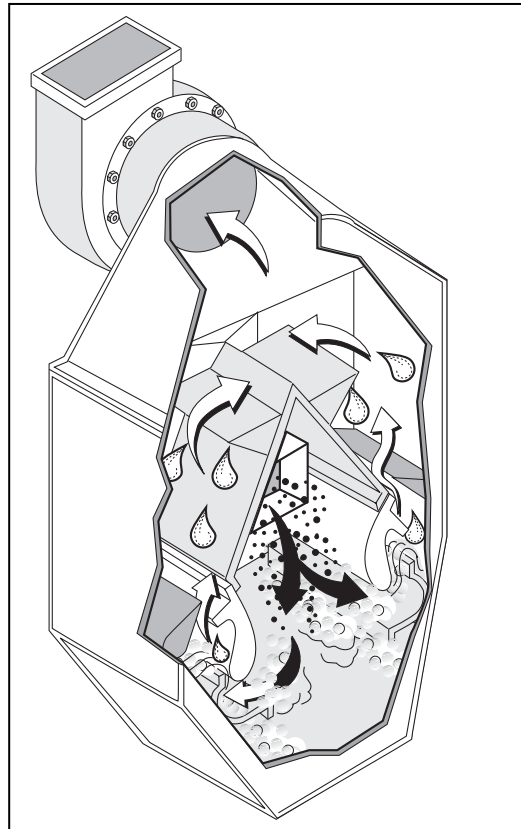


Figure 3-15. Self-induced spray orifice scrubber

Particulate matter collected in the scrubber forms a sludge that must be disposed of. Sludge disposal involves removing and recycling large amounts of liquid, from 3.5 to 4.2 L/m<sup>3</sup> (25 to 30 gal/1000 acfm). Some designs incorporate a sludge separation and removal system inside the scrubber to minimize the amount of water that must be removed. The water level inside the scrubber must be maintained during the sludge separation and removal cycle so that the unit can operate efficiently.



### **Particle Collection**

Large particles in the incoming exhaust stream are collected as they impinge on the surface of the pool. Smaller particles are collected as they impact on the droplets produced by the high-velocity gas skimming over the liquid. Overall particle collection in an orifice scrubber depends on the level of the liquid. The level of the liquid determines the gas velocity (and, thus, the pressure drop) through the orifice. If the liquid level is low, gas velocities decrease because the orifice opening is larger. Lower velocities produce fewer droplets and ones that are larger in size, decreasing particle collection. A *turn-down* of the system, or reduction in gas volume, will also result in less atomization and produce larger droplets. It is recommended that gas velocities should not fluctuate by more than 10 to 15% of design values to provide maximum effectiveness (Bethea 1978).

### **Gas Collection**

Orifice scrubbers are rarely used for absorption (McIlvaine Company 1974). However, because orifice scrubbers provide both thorough mixing of the gas and liquid, and large liquid-surface contact areas (many tiny droplets), these devices can be effective for removing gaseous pollutants that are already very soluble in the liquid. In reactive scrubbing, the gaseous pollutants chemically react with the scrubbing liquid. These reactions occasionally produce scale or sludge that can plug scrubber internals. The relatively large orifice openings will not plug as easily as those in plate towers.

### **Maintenance Problems**

The greatest problem for orifice scrubbers is maintaining the liquid at the proper level for a constant gas flow rate. Orifice scrubbers are designed to operate with a specific liquid level for a given gas velocity. If the gas flow decreases (or the liquid level decreases), less atomization occurs, thus reducing collection efficiency. If gas flow rate increases too much, it is possible to blow the liquid chamber dry (Bethea 1978). Systems are generally designed to operate at the upper end of the process exhaust rate and to introduce makeup air if the exhaust stream volume (velocity) becomes too low. Controlling the liquid level is much more difficult than maintaining a constant exhaust gas flow rate because of the turbulent condition of the water.

## Summary

Orifice scrubbers are medium-energy devices with moderate collection efficiencies. The pressure drops across these devices are usually between 5 and 25 cm (2 and 10 in.) of water. The relatively large openings enable them to accommodate exhaust streams with high concentrations of particulate matter. Plugging by sticky or stringy material and scale buildup are not major problems. Because the gas stream is forced through a pool of liquid to create liquid droplets, spray nozzles are not necessary.

Orifice scrubbers are used mainly on metallurgical processes (crushing, screening, grinding, etc.), where the particles generated are mostly above 1  $\mu\text{m}$  in diameter. Removal efficiencies depend on exhaust stream velocities. Reduction in exhaust stream velocities or liquid levels in the device will cause a reduction in collection efficiency. Table 3-6 lists operating characteristics of orifice scrubbers.

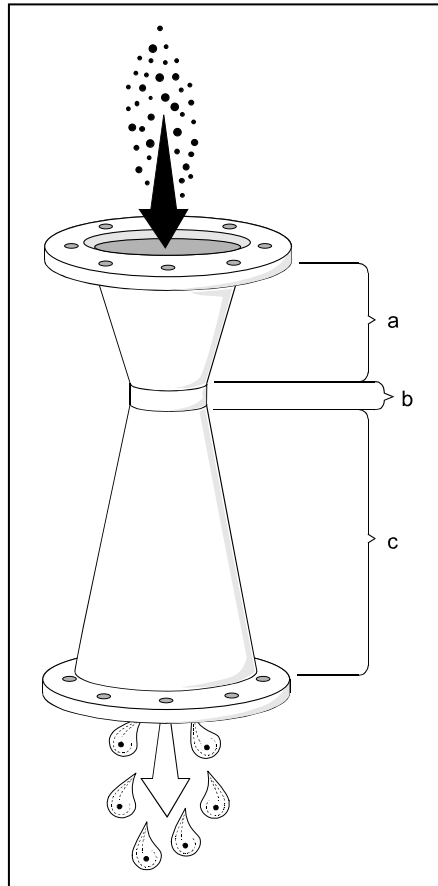
Table 3-6. Operating characteristics of orifice scrubbers					
Pollutant	Pressure drop ( $\Delta p$ )	Liquid-to-gas ratio (L/G)	Liquid-inlet pressure ( $p_L$ )	Removal efficiency	Applications
Gases	5-25 cm of water  (2-10 in. of water)	0.07-0.7 L/m <sup>3</sup> (0.5-5 gal/1000 ft <sup>3</sup> )	Not applicable (nozzles are not used)	Limited to very soluble gases or reactive scrubbing	Mining operations Rock products industries Foundries Pulp and paper industries
Particles		1.3-5.3 L/m <sup>3</sup> (10-40 gal/1000 ft <sup>3</sup> ) for sludge removal and recycle		0.8-1 $\mu\text{m}$ diameter	Chemical process industries

*To test your knowledge of the preceding section, answer the questions in Part 3 of the Review Exercise.*

# Review Exercise

## Part 1

1. Label the following sections of the venturi.



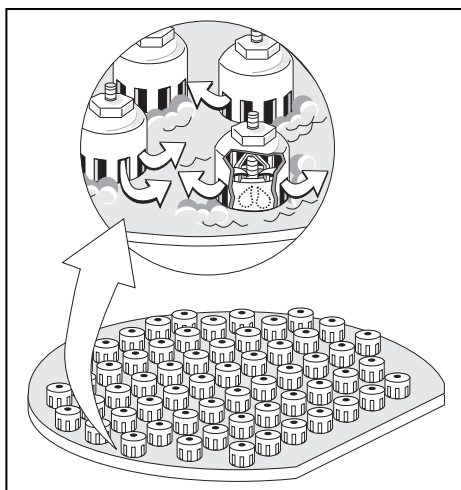
2. In a venturi scrubber, the majority of pollutant removal occurs in the:
  - a. Converging section
  - b. Throat
  - c. Diverging section
3. A venturi scrubber in which liquid is introduced above the throat section:
  - a. Increases the likelihood of dust buildup on the throat
  - b. Reduces dust buildup on throat surfaces
  - c. Has the highest gas absorption capabilities of any wet collector
  - d. None of the above

4. Many venturi scrubbers have devices by which the throat area can be varied to maintain:
  - a. Gas velocity through the throat
  - b. Pressure drop
  - c. Turbulence in the throat
  - d. All of the above
5. True or False? Venturis are the most commonly used scrubber for particle collection.
6. In a venturi scrubber, particle collection increases with an increase in \_\_\_\_\_.
7. To be effective in collecting particles, venturi scrubbers must operate at a pressure drop of:
  - a. 10 cm (5 in.) of water
  - b. 50 cm (20 in.) of water
  - c. 150 cm (60 in.) of water
  - d. Any of the above
8. Venturi scrubbers are generally limited in their capability of removing gaseous pollutants because of:
  - a. The short gas-liquid contact time
  - b. Low L/G ratios
  - c. Small liquid droplets formed in the throat
  - d. All of the above
9. Venturi scrubbers are useful for simultaneous gas and particle removal, especially when:
  - a. Scale buildup could be a problem
  - b. A high concentration of dust is in the exhaust stream
  - c. The dust is sticky or has a tendency to plug openings
  - d. The gaseous pollutant is very soluble
  - e. All of the above
10. To maximize gas collection in a venturi scrubber, the pressure drop is \_\_\_\_\_ and the L/G ratio is usually \_\_\_\_\_ when compared to operating conditions for particle collection.
  - a. Increased, increased
  - b. Increased, decreased
  - c. Decreased, increased
  - d. Decreased, decreased
11. The primary maintenance problem for venturis is:
  - a. Plugging due to the many internal parts
  - b. Weeping due to low gas flows
  - c. Abrasion of the throat due to the high gas velocities
  - d. All of the above

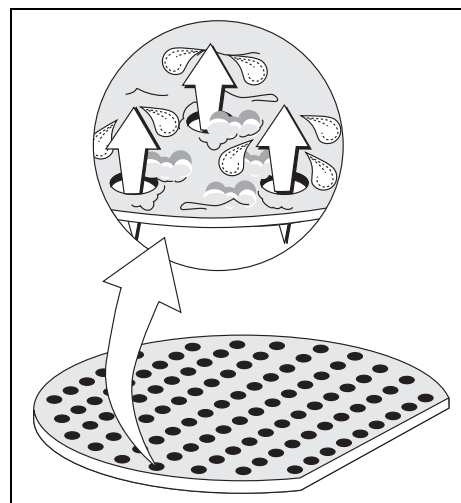
12. What does flooding the elbow between the venturi and the separator reduce?
- Abrasion of the elbow
  - Velocity of the gas stream
  - Plugging in the elbow
  - Pressure drop across the device
13. In general, venturis are more effective in removing \_\_\_\_\_ than they are in removing \_\_\_\_\_.
- Gases, particles
  - Particles, gases

## Part 2

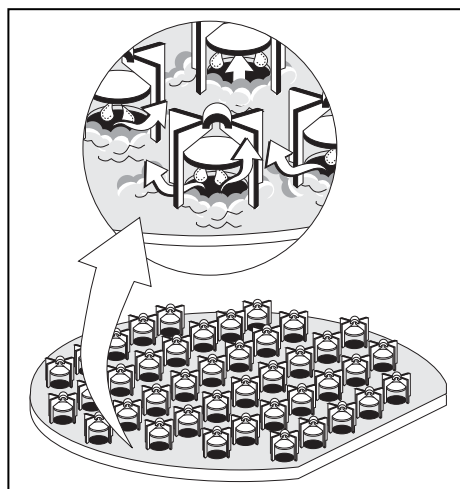
14. Name each of the following designs for plates in plate towers.



(a)



(b)



(c)

15. True or False? For particle collection, efficiency does not significantly increase by increasing the number of plates in a plate tower.
16. In a plate tower, particle collection can usually be enhanced by \_\_\_\_\_ the hole size and/or \_\_\_\_\_ the number of holes per plate.
- Increasing, increasing
  - Increasing, decreasing
  - Decreasing, increasing
  - Decreasing, decreasing
17. For gaseous pollutant collection in a plate tower, absorption can usually be enhanced by:
- Adding plates
  - Increasing the amount of liquid
  - Both a and b
18. If the plates in a tower are not \_\_\_\_\_, gas-liquid contact can be reduced, thus reducing collection efficiency.
- The same size
  - Level
  - Staggered
  - Omitted
19. In plate towers, liquid dripping through the holes in the plates, due to a low gas velocity, is referred to as:
- Flooding
  - Dropsy
  - Weeping
  - Drooling
20. List at least three common operational problems associated with plate towers.
- \_\_\_\_\_
- \_\_\_\_\_
- \_\_\_\_\_

### Part 3

21. Although orifice scrubbers are produced in a variety of configurations, all are designed so that the exhaust gas stream:
- Is split into two streams
  - Travels concurrently with the liquid stream
  - Breaks through a pool of liquid
  - None of the above
22. True or False? In an orifice scrubber, all particles are collected as they impinge on the surface of the liquid.

23. The exhaust gas velocity (thus, the pressure drop) in an orifice scrubber is dictated by the:
- a. Adjustable throat
  - b. Level of liquid
  - c. The plant foreman
  - d. Precise calculations
24. In orifice scrubbers, a reduction in the design exhaust gas flow rate results in:
- a. An increase in gas collection
  - b. An increase in particle collection
  - c. Less atomization and production of larger liquid droplets
  - d. Both a and b
25. True or False? An orifice scrubber is capable of operating over a wide range of gas flow rates.
26. True or False? Orifice scrubbers are not primarily used for gas absorption.
27. The greatest problem with orifice scrubbers is:
- a. Maintaining the proper liquid level
  - b. Plugging
  - c. Scale buildup
  - d. Erosion
28. True or False? Plugging and scale buildup are not major operating problems with orifice scrubbers.

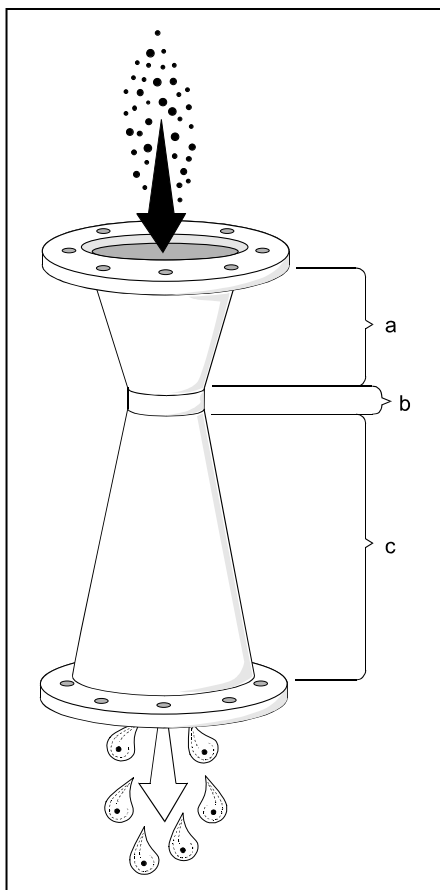




## Review Exercise Answers

### Part 1

1.
  - a. Converging
  - b. Throat
  - c. Diverging



2. **b. Throat**  
In a venturi scrubber, the majority of pollutant removal occurs in the throat.
3. **b. Reduces dust buildup on throat surfaces**  
A venturi scrubber in which liquid is introduced above the throat section reduces dust buildup on throat surfaces.
4. **d. All of the above**  
Many venturi scrubbers have devices by which the throat area can be varied to maintain:
  - Gas velocity through the throat
  - Pressure drop
  - Turbulence in the throat

5. **True**

Venturis are the most commonly used scrubber for particle collection.

6. **Pressure drop**

In a venturi scrubber, particle collection increases with an increase in pressure drop.

7. **d. Any of the above (depending on the specific scrubber design and application)**

To be effective in collecting particles, venturi scrubbers can operate at the following pressure drops (depending on the specific scrubber design and application):

- 10 cm (5 in.) of water
- 50 cm (20 in.) of water
- 150 cm (60 in.) of water

8. **a. The short gas-liquid contact time**

Venturi scrubbers are generally limited in their capability of removing gaseous pollutants because of the short gas-liquid contact time.

9. **e. All of the above**

Venturi scrubbers are useful for simultaneous gas and particle removal, especially in the following situations:

- Potential problem of scale buildup
- A high concentration of dust is in the exhaust stream
- The dust is sticky or has a tendency to plug openings
- The gaseous pollutant is very soluble

10. **c. Decreased, increased**

To maximize gas collection in a venturi scrubber, the pressure drop is decreased and the L/G ratio is usually increased when compared to operating conditions for particle collection. Decreasing the pressure drop will result in a decrease in velocity and an increase in residence time. Higher liquid rates will provide better potential gas solubility.

11. **c. Abrasion of the throat due to the high gas velocities**

The primary maintenance problem for venturis is abrasion of the throat due to the high gas velocities.

12. **a. Abrasion of the elbow**

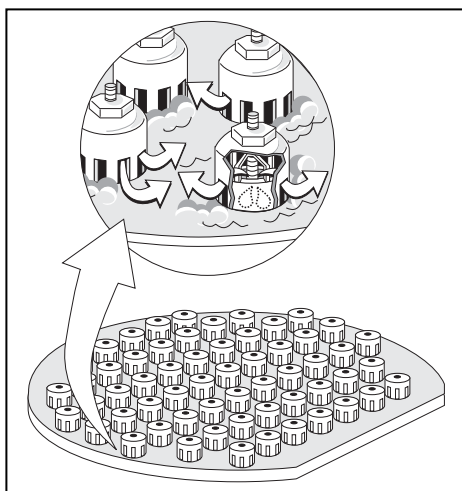
Flooding the elbow between the venturi and the separator reduces abrasion of the elbow.

13. **b. Particles, gases**

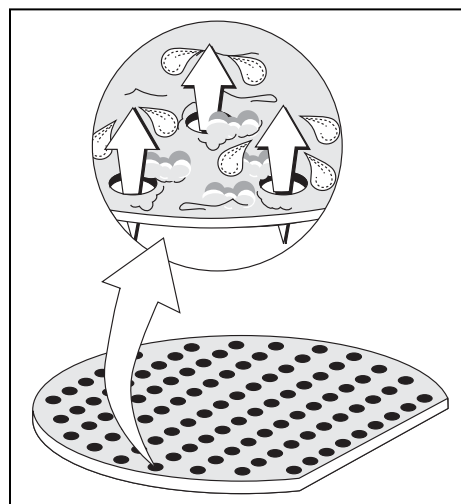
In general, venturis are more effective in removing particles than they are in removing gases.

**Part 2**

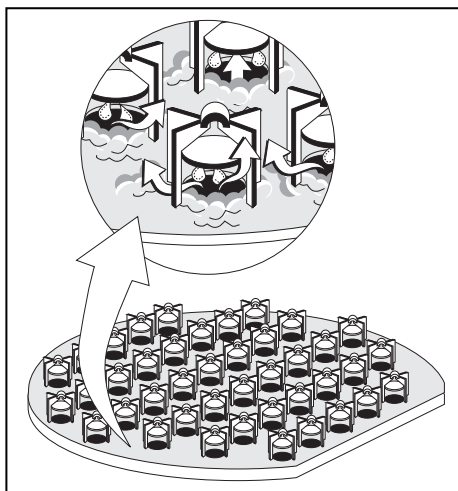
14. a. Bubble-cap  
b. Sieve  
c. Valve



(a)



(b)



(c)

15. **True**

For particle collection, efficiency does not significantly increase by increasing the number of plates in a plate tower.

16. **c. Decreasing, increasing**

In a plate tower, particle collection can usually be enhanced by decreasing the hole size and/or increasing the number of holes per plate. Both of these changes result in better gas-to-liquid contact. However, they also add more resistance (increase pressure drop) and therefore higher operating costs.

17. **c. Both a and b**

For gaseous pollutant collection in a plate tower, absorption can usually be enhanced by adding plates and increasing the amount of liquid.

18. **b. Level**

If the plates in a tower are not level, gas-liquid contact can be reduced, thus reducing collection efficiency.

19. **c. Weeping**

In plate towers, liquid dripping through the holes in the plates, due to a low gas velocity, is referred to as weeping.

20. **Weeping**

**Plugging**

**Flooding**

Three common operational problems associated with plate towers are weeping, plugging, and flooding.

**Part 3**

21. **c. Breaks through a pool of liquid**

Although orifice scrubbers are produced in a variety of configurations, all are designed so that the exhaust gas stream breaks through a pool of liquid.

22. **False**

In an orifice scrubber, only large particles are collected as they impinge on the surface of the liquid. Small particles are collected by liquid droplets produced by the exhaust stream.

23. **b. Level of liquid**

The exhaust gas velocity (thus, the pressure drop) in an orifice scrubber is dictated by the level of liquid.

24. **c. Less atomization and production of larger liquid droplets**

In orifice scrubbers, a reduction in the design exhaust gas flow rate results in less atomization and production of larger liquid droplets which could potentially lower the gas and/or particle collection efficiency.

25. **False**

Exhaust gas velocities should not fluctuate greatly in orifice scrubbers.

26. **True**

Orifice scrubbers are NOT primarily used for gas absorption.

27. **a. Maintaining the proper liquid level**

The greatest problem with orifice scrubbers is maintaining the proper liquid level.

28. **True**

Plugging and scale buildup are not major operating problems with orifice scrubbers because of their open design.

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